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DAYLIGHTING AS A DESIGN AND ENERGY STRATEGY: OVERVIEW OF OPPORTUNITIES AND CONFLICTS

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ABSTRACT

This paper reviews the potentials and problems associated with using daylight both to improve visual performance and interior aesthetics and to reduce electrical lighting energy consumption and peak electric loads. Use of daylighting as a design strategy is not always synonymous with effective use of daylighting as an energy-saving strategy unless both approaches are jointly pursued by the design team. We review criteria for visual performance, disability and discomfort glare, historical perspectives on daylight utilization, building form as a limit to daylight penetration, beam sunlighting strategies, luminous efficacy of daylight versus efficient electric light sources, comparative thermal impacts, peak load and load management potential, and non-energy benefits. Although the energy benefits of daylighting can be oversold, we conclude that in most cases a solid understanding of the energy and design issues should produce energy-efficient and pleasing working environments.

INTRODUCTION

Throughout history, windows have provided view out of buildings and illumination in what otherwise would have been dark interiors. Building designers quickly mastered the details necessary for using daylight effectively in buildings. A review of the patent literature at the turn of the last century suggests that some effort was expended in the design of windows and skylights which would allow more extensive use of sunlight and daylight in buildings. Before these technologies matured, however, a radical innovation, the electric light, destined them for obscurity in old patent files. Yet architects have continued to use natural light as a supplement to electric lighting design, the primary motivation being to enhance the quality of light in the building and the experience of working in the building.

Expensive oil has forced us to reconsider more practical uses for daylighting in buildings. We now look to daylight not only as a source of illumination and an aesthetic element in buildings, but also as a strategy for reducing electric energy consumption and electric loads. In modern commercial buildings, energy consumption for lighting is frequently the largest single energy use. This fact, plus the contribution of electric lighting and cooling loads to peak electrical demands, emphasizes the importance that daylight might have as an energy-efficient design strategy. It is important to realize, however, that effective use of daylight as a lighting design strategy is not always synonymous with effective use of daylight as an energy-conservation strategy. Certainly, there is no inherent conflict between the two, but success in one does not necessarily produce success in the other. Our cumulative experience with daylighting is rather large from the perspective of lighting design. Our quantitative experience using daylight to reduce energy consumption is rather limited. It is important to define the goals and objectives of daylighting as both a design and an energy strategy in order to evaluate the success or failure of a building design in meeting those goals.

There are four primary goals for the use of daylight in most buildings:

1. Energy Savings: Minimize use of nonrenewable energy resources for lighting, minimize the costs associated with making use of daylight, and optimize the energy-related functions of windows and skylights.

2. Load Management: Control electric lighting loads so as to minimize costs for the building owner or operator and to maximize benefits for the utility that must meet those loads.

3. Lighting Quality and Visual Performance: Quality and quantity of daylighting and electric light must meet requirements for visual performance. Occupant productivity is a critical concern in most commercial buildings, and lighting quality should encourage and enhance productivity.

4. Design and Aesthetics: Daylighting design should improve the experience of working in a space, provide appropriate view, and contribute to a pleasant and healthful working environment.

There is no inherent conflict among these four directives. However, few buildings have successfully integrated all four concerns. The danger in designing for the first two energy issues is that lighting quality and aesthetics may suffer. Conversely, successful achievement of lighting quality does not guarantee an energy-efficient building. Since the energy concerns are more easily quantifiable, there is a danger that we will overlook lighting quality in our rush to squeeze the Btu per square foot rating ever lower. We must remember that we light the interior of a building not for the sake of the building, but for the visual needs of people. Any proper accounting of the effectiveness of daylighting must assess the impact on human energy resources as well as on building energy consumption.

We now consider several topics that are central to effective use of daylighting and that are sufficiently complex to cause some confusion regarding optimal design strategy.

1. DAYLIGHTING POTENTIALS AND CONSTRAINTS

Concern for daylight will influence design decisions from the scale of urban planning down to details such as the color of carpet. Decisions made at any level may limit or enhance daylighting potential. At the large end of the scale, urban planning influences the daylight available at a building site and constrains length/width ratios and height. For a given building on a given site, decisions regarding massing, shape, and form influence the fraction of floor area that will have access to daylighting. Size of the building is a critical factor. The total task area to be illuminated will be a function of total floor area, whereas the potential for admitting daylighting into the building will be a function of the exposed skin of the building. The relationship between these two parameters sets some fundamental constraints on the fraction of the building which may be daylit. In general, diffuse light from a window will provide adequate working illumination at a depth of approximately one to three times the height of the window opening. This fundamental limit had a powerful effect on office dimensions in older buildings. In the first half of the century, designers produced highly articulated building shapes with wings, fingers, light courts, and other design layouts having windows that admitted light to the majority of usable space in the building. These designs also enhanced natural ventilation before air conditioning existed. Floor-to-ceiling heights characteristically were greater than they are today, further enhancing daylight penetration into the space. Courtyards, atria, and lightwells provided vertical penetration of light to supplement sidelighting.

Beamed sunlighting strategies in principle remove any practical limitation on the depth of daylight penetration. Despite the extensive patent literature on the subject, the major historical approaches to using reflected sunlight have been to use glass block and light shelves. Both are currently being re-examined, as are more elaborate schemes for reflecting and refracting sunlight. Although many of these are technically achievable, they may not prove to be practical or economically feasible.

The priorities of daylighting strategies will generally differ between new and retrofit buildings, reflecting the physical constraints of an existing building versus the relative freedom of new construction. A more fundamental distinction might be made regarding daylighting strategies for either case. Here we consider two extreme approaches. The first is known as the "Take What You Can Get" approach. In this case the designer tackles the most obvious opportunities for potential lighting savings in a building. These may include corridors, lobbies, perimeter offices, stairwells, and other locations where either daylight is easily accessible or the visual requirements are not severe. In these cases, daylight will generally supplement electric lighting, which will be the primary design strategy. The other extreme might be termed the "Daylighting Showcase" approach. In this case, daylighting is the central lighting strategy for the building. Attempts are made to daylight the maximum feasible floor area as well as to provide daylight for the maximum number of hours during the year. Electric light is added when daylight is insufficient to meet visual performance needs. This approach generally requires more sophisticated architectural control of the daylight and a knowledge of lighting controls.

2. REAL ENERGY AND LOAD SAVINGS

All buildings that have windows or skylights can be said to be daylit. But only those having appropriate lighting controls will actually save electrical energy or reduce electrical demand. Daylighting strategies generally save some percentage of total lighting energy consumption in a building. Translating that percentage into dollars and cents requires defining the efficacy of the electric lighting system. The less efficient the electric lighting, the more impressive the daylighting savings will appear. However, very efficient electric light sources with state-of-the-art lighting controls can significantly reduce electric lighting energy consumption, even in a nondaylit space. When compared to efficient electric lighting, daylighting savings in the perimeter zone may be modest in terms of kilowatt-hours per year. Those smaller savings may not be sufficient to justify extensive investment in lighting controls and any sun or glare control that may be necessary.

Lighting controls are becoming popular in many new buildings. The desire is to control illumination levels throughout the day to meet occupancy requirements and to allow levels to be adjusted spatially to meet different task requirements. Many of these systems will provide daylighting control at little or no extra cost. One must also accept the fact that daylighting strategies would not be credited with saving energy in an unoccupied office where the lights would have been turned off anyway. Improved high-efficiency lamps, better fixtures, and more sophisticated lighting controls are rapidly changing some of the strategies and details of lighting design. These trends affect the use of daylight in ways we are only beginning to understand.

Responsive lighting controls will reduce electrical demand in buildings and improve load management opportunities. Since owners of many commercial building pay large demand charges, this load management can be translated into additional economic savings. The relative importance and economic benefit daylighting has for load management will depend on building type and size, geographical location, and the utility rate structure. Utilities that have the smallest generating reserve margin and the most difficulty in siting and building new plants should be most responsive to daylighting's load management potential. Their concern for providing for growth in electrical load demand often will be reflected in high demand charges.

Substituting daylight for electric lighting clearly will reduce electrical consumption in a building. Daylighting, however, will also affect heating and cooling loads. If window size must be increased to provide adequate daylighting, what are the net thermal gains or losses associated with this increased window size? Once again, the answers are complex, depending upon building type, orientation, operating characteristics, and location. Reduced electric consumption from daylighting will frequently increase winter heating loads. This should not be a significant problem because it will generally be cheaper and more efficient to supply increased heating loads directly from the central heating system rather than indirectly from the building lighting system. Electric lights as resistant heaters will generally be neither the most cost-effective nor the most efficient heating source in the building.

The impact of daylighting on cooling loads is more difficult to determine. If we compare the efficacy of daylight to that of electric sources we conclude that daylight is slightly more efficacious. Light from the sun and sky generally provides between 90 and 120 lumens per watt. Good fluorescent systems will produce in the range of 60 to 80 lumens per watt, and HID systems used indoors may provide 80 to 100 lumens per watt. However, this comparison can be misleading because daylight intensity changes with time and varies with location in a room. While an electric lighting source can be carefully controlled to provide desired intensity at specific locations and constant intensity during the time that the light is desired, daylight cannot. In order to provide adequate footcandles deeper in a space, excessive footcandles may have to be introduced into portions of the space. While this may be harmless from the lighting point of view, it may increase thermal loads. Furthermore, if design is based upon a typical or average daylight value, there will be times when there is significantly more daylight than the average. Once again, the light may be welcome but the associated heat gain may not. If sized to provide adequate daylight on overcast days, the window will need effective operable shading systems to reduce direct sun on clear days. Consistent maintenance and operation of these shading systems will be necessary to minimize cooling loads. Little evidence exists to suggest that daylighting saves more cooling energy on a seasonal basis than does an efficient electric lighting system.

The efficacy of daylight can be increased by using selective transmitting glass. Conventional blue-green tinted glass and newer types of reflective coatings, which should reach the market soon, selectively transmit the visible energy of sunlight and absorb or reflect the solar infrared wavelengths. This can result in an even higher luminous efficacy for daylight. However, lighting hardware also continues to improve. The balance between daylight and electric lighting in terms of thermal efficacy probably will not be radically shifted by new technology in the coming years, although each will continuously improve. In any specific building a choice between the two may be clear-cut, but in general efficient daylighting design should have approximately the same thermal impact as efficient electric lighting design.

3. LIGHTING QUALITY

The footcandle is a common measure of light flux striking a surface. By itself it says little about the ability to see an object or perform a visual task. For years the lighting design community has debated the relative merits of various metrics for evaluating visual performance and the best way to determine how much light should be provided for various visual tasks. The useful results of that debate center around aspects of lighting quality which either contribute to, or subtract from, our ability to perform visual tasks effectively. Glare is an aspect of lighting quality which frequently comes to mind when discussing daylight. There are two types of glare. We have all experienced "disability glare," a situation in which it is difficult to see print on a glossy page if the light source is in a certain position. These "veiling reflections" reduce the contrast between print and background page and thus reduce our ability to see the print. The intensity of veiling reflections depends upon the quality of the visual task and the location of the light source. It is the latter that building designers can generally influence. A simple test to determine if light fixtures, windows, or skylights will significantly contribute to veiling reflections can be conducted using a mirror. If a mirror is placed at the task location, any light source seen in the mirror will contribute to veiling reflections. Since windows admit light from the side, they generally reduce glare and improve visibility compared to overhead light sources. A corollary, however, is that occupants generally should not face windows, but rather be oriented perpendicular to daylight sources.

"Discomfort glare" results from a light source that is in the field of view or just outside the field of view and is very bright relative to task or surroundings. After the eye adapts to the bright source, it takes time to readjust to the reduced luminance of the task. A typical task in an office which is lit to 50 footcandles may have a luminance of 40 foot-lamberts. A hazy sky seen through a window could produce 2000 foot-lamberts, or 50 times the luminance of the task. Architecturally, brightness differences will be less annoying if there are smooth transitions between them. Splayed window details, for example, soften the gradient between the view of the inside surface of the wall and the outdoors. Higher reflectance interiors are generally better than dark interiors for a similar reason. There are calculation procedures for determining when glare reaches a discomfort level. The impact of glare on daylighting as an energy-saving strategy develops from the observation that, given dimmable controls, office occupants may choose to increase electric light levels indoors as the outdoors gets brighter. The brain may desire reduced energy consumption, but the eye and hand will instinctively respond to balance contrast.

There are a number of well known architectural responses that can moderate glare problems. Tinted or lightly reflecting glass may be an appropriate solution in some circumstances. A wide range of architectural and operable shading systems exists to control both solar gain and glare. Many of these are manually operated, but increasing numbers are becoming available with automatic operating systems. Another approach is to separate the view function of the window from the light admittance function, for instance by providing a small tinted vision strip low in the wall and an appropriately shaded clerestory window above. Another architectural solution is to use light shelves or interior louvre systems to block direct view of the sky, diffuse the intensity of incoming light, and redirect sunlight and skylight deeper into the room.

Direct sunlight generally should be excluded from most building spaces where visual tasks are to be performed. Appropriate use of direct sunlight in less critical areas such as lobbies, corridors, and other circulation spaces adds visual diversity and a dynamic element to interior spaces. In these circumstances direct sunlight can be used consistent with proper management of thermal gains and losses. In the winter this may mean admitting as much sunlight as possible while maintaining visual quality; in the summer it will generally mean minimizing direct sunlight. In all cases care and thought must be given to introducing daylight into building interiors.

SUMMARY AND CONCLUSIONS

Given the appealing potentials and the associated cautions for daylight utilization, what can one conclude and how should one proceed? First, any use of daylight in a space should be based upon a critical review of lighting requirements for visual performance and design aesthetics. Based upon those lighting criteria and the energy consumption goals for the building, one can select basic daylighting/electric lighting design strategies to explore in more detail. Although daylighting competes with good electric lighting design, it is a friendly rivalry that challenges the inventive genius of designers and should not be viewed as a negative force. Further, although the focus of this discussion has been on lighting, critical decisions regarding the use of daylighting in buildings clearly will impact, and be impacted by, related decisions about circulation, structure, HVAC systems, and most other building elements. This interrelationship of daylight with other systems also should be looked upon as an opportunity rather than a problem.

When we examine the cost-effectiveness of daylighting, the energy savings alone may be insufficient to justify daylighting. However, it may turn out that costs incurred for daylighting (such as an extended building form) may enhance natural ventilation and broaden the basis for calculating cost-effectiveness. Furthermore, in addition to economic benefits resulting from energy savings and responsiveness to time-of-day rates and peak demand charges, daylight may save the building owner money over the lifetime of the building by providing a "failure tolerance" that allows a building to continue operating should there be a local or large-scale interruption in electrical supply. The cost of worker time is so high that a single hour of productive time that otherwise would have been wasted approximately equals the entire annual lighting energy consumption figure for a building on a square-foot basis.

In closing, one should not hesitate to build the strongest possible case for the use of daylight in buildings. Effective use of daylight promises reduced operating costs due to energy and demand savings, improved visual quality, and increased amenity and well-being in the indoor environments in which many of us spend the largest fraction of our waking hours.

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